2010

Prediction of Spatial and Temporal Distribution of Expiratory Droplets in an Aircraft Cabin

Jitendra Gupta
Purdue University

Chao-Hsin Lin
Boeing Commercial Airplanes

Qingyan Chen
Purdue University

Prediction of Spatial and Temporal Distribution of Expiratory Droplets in an Aircraft Cabin

Jitendra K. GUPTA[1*], Chao-Hsin LIN[2], Ph.D., Qingyan CHEN[1], Ph.D.

[1]National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE), School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907-2088, USA,

[2] Environmental Control Systems, Boeing Commercial Airplanes, Everett, WA 98203, USA

[*]Corresponding Author Contact: jgupta@purdue.edu

ABSTRACT

The present study investigated the unsteady transport of droplets exhaled by an index passenger in an aircraft cabin using the CFD simulations. A section of twin aisle cabin with seven-rows and full occupancy was studied. It was found that the expiratory droplet cloud was initially dense and moved to specific zones. The droplet concentrations were higher in these zones. The droplet concentration then reduced due to dispersion and droplet removal from the outlets. The droplets were mostly contained in the front, back and row of the index passenger. It was observed that the perfectly mixed conditions can be used to extend the information on the droplet concentration beyond 3 minutes. It was found that the droplet concentration information obtained from a single exhalation CFD simulation can be superimposed to obtain the information for multiple exhalations. A routine was developed to find the droplets inhaled by every passenger for 2-hours of air travel.

1. INTRODUCTION

Indoor environments such as, the office spaces, auditoriums, hospitals, and public transportation vehicles have occupants seated closely for several hours. These environments are confined with low air exchange rates compared to outdoors. Thus the chances of an infection spread to fellow occupants from an infected occupant suffering from contagious diseases such as, influenza or tuberculosis, are higher in indoor environments compared to outdoors. The droplets exhaled by the infected occupant are the carrier of contagious agents. Therefore, it is important to study the transport of expiratory droplets in indoor environments to identify the zones under high risk.

Computational Fluid Dynamics (CFD) models are widely used to predict the contaminant transport in indoor environments (Zhang et al., 2009 and Wan et al., 2009). The CFD models are inexpensive, fast and more flexible to changes compared to experiments. The CFD models can provide detailed information on airflow, temperature distribution and contaminant transport but need precise boundary conditions. Appropriate transport equations need to be solved to obtain an accurate solution. The present study used the CFD simulations to predict the transport of droplets exhaled by an infected (index) passenger in an aircraft cabin. The boundary conditions for the exhalation events were obtained from experiments (Gupta et al., 2010)

An air travel could last from one to 20 hours. During this period, the index passenger can exhale droplets through various and multiple exhalations such as, periodic breathing, coughing or talking. It took 4 weeks to predict the droplet movement for 4 minutes of time in a seven-row section of a twin aisle cabin using the CFD methods on a 8 parallel high speed processor units. Thus performing these calculations for an air travel of even one hour is not practical. The investigations developed methods based on the findings from the CFD simulations of four minutes to extend the data on the droplet movement for realistic air travel durations and multiple exhalation scenarios.

2. RESEARCH METHODS

The spatial and temporal distribution of droplets exhaled from the breathing of an index passenger seated in the center of an aircraft cabin was studied for a seven-row section of an aircraft. The CFD simulations were performed using a commercial software FLUENT. Figure1 and table 1 show the boundary surfaces and the corresponding boundary conditions.

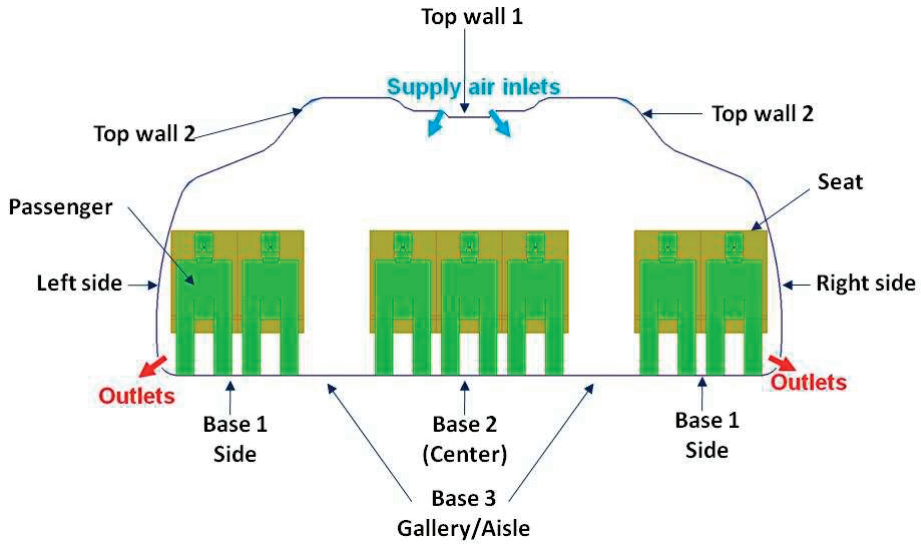

Figure 1. Boundary surfaces for the cabin

Table 1. Boundary conditions

Surface	Flow	Temperature (°C)	Humidity	Droplet fate
Human body and mouth	No slip	31	zero diffusive flux	Reflect
Seat		Adiabatic	zero diffusive flux	Reflect
Top Wall (between the inlets)		23.8	zero diffusive flux	Reflect
Top Wall		26.4	zero diffusive flux	Reflect
Left and Right Side wall		24.5	zero diffusive flux	Reflect
Base (Side)		24.4	zero diffusive flux	Reflect
Base (center)		25.1	zero diffusive flux	Reflect
Aisle		24.1	zero diffusive flux	Reflect
Inlets	2.88 m/s (x=0, y= -0.3,z=±0.95)	19.3	0.003 (20%RH)	Escape
Outlets	Outflow			Escape
Nose of the passenger	No slip (Steady) / Gupta et al., 2010 (Unsteady)	31 (Steady)/ 33 (Unsteady)	0.007 (50% RH)	Reflect
Ends of the cabin	Periodic			

The expiratory droplets were tracked using the Lagrangian approach. It was assumed that the droplets exhaled during breathing were of one size (0.4 μm) and a total of 10^3droplets/liter were exhaled (Fabian et al., 2009 and Fairchild and Stampfer, 1987). The RNG k-ε turbulence model was used. PRESTO scheme was used for pressure discretization, while second order schemes were used to discretize the momentum and energy equations.

A steady state airflow was first obtained and used as an initial condition for the expiratory droplet transport case. The variation in the number of expiratory droplets with time was monitored in a cubical volume of 0.028 m^3 (1ft x 1ft x 1 ft) around the nose of each passenger.

The variation in droplet concentration in these zones indicated that the droplets got well mixed in the domain in about 3 minutes. Therefore, the averaged droplet fraction, c(t) can be obtained using perfectly mixed conditions and is given by equation (1).

$$c(t) = \frac{c_t(180)\exp(Q(t-180)/\ V)}{V} \tag{1}$$

Where $c_t(180)$ is the total droplet fraction at 180 seconds i.e. the total number of droplets in the remained in the cabin at 180s divided by the total number of droplets exhaled, Q is the total supply flow rate, and V is the volume of the cabin.

The index passenger can exhale droplets through multiple breathing over several hours of air travel. It is not practical to carry out the CFD simulations for all such exhalations. It is thus required to investigate the differences in the droplet trajectories exhaled during various breathing cycles. A case with 10 consecutive exhalations from the breathing of the index passenger was studied to identify the differences. It was observed that the droplets from all the exhalations followed similar trajectories, even though the airflow in the cabin was unsteady. This indicated that the bulk flow in most of the domain was almost steady. It is thus proposed that the information on the transport of the droplets exhaled from a single breath CFD simulation can be superimposed multiple times, to obtain the droplet distribution in the cabin for the multiple breathing exhalation case. The concentration of droplets in any zone at any time can be obtained by summing up the concentrations of the droplets in the zone from all the exhalations taken place until that time provided with a time shift and is given by equation (2).

$$C_i(t) = \sum C_{b,i}(t - t_j) \tag{2}$$

Where,

$C_i(t)$: Total number of the expiratory droplets in the zone around the i^{th} passenger

$C_{b,i}(t\text{-}t_j)$: Number of expiratory droplets in the zone at time $t\text{-}t_j$ due to breathing started at t_j.

The concentration $C_{b,i}$ can be obtained from the CFD simulations on the transport of the droplets exhaled from a single breath and using the perfectly mixed conditions.

A hypothetical case with the index passenger exhaling the droplets regularly through breathing for a 2 hours of flight was analyzed. The droplet distribution for the 2 hour flight case was obtained by using

1) The method to extend the data of a single breath 3 minute CFD simulation using the perfectly mixed assumption

2) The method to extend it to multiple breathing exhalation using superimposition.

The total amount of droplets inhaled by each passenger during the 2 hour flight was calculated by integrating the breathing profile of each passenger with the droplet concentration in the vicinity of his breathing zone as given by equation (3).

$$r_i(t) = \sum q_i(t)\ \ c_i(t)\ \ \Delta t \tag{3}$$

Where,

q_i is the rate of inhalation (volume/time) for the i^{th} passenger and is zero during exhalation and c_i is the concentration of droplets in the vicinity of the i^{th} passenger

3. RESULTS

Figure 2 shows the airflow at the cross sectional and the longitudinal planes passing through the index passenger (seat 4D, see Figure 3), and the longitudinal plane passing through the aisle. The cold air from the supply inlets flowed to the sides along the top wall, and a part of it existed through the outlets located at the bottom sides. The other part and the thermal plumes created two large re-circulations in the cross section. The airflow currents clearly indicate the mixed convection in the cross section. It should be noticed that the flow was approximately symmetrical about the centerline (longitudinal direction). The airflow current on the top were strong in the lateral direction (forced convection). The airflow near the vicinity of the passengers in the center column was due to the thermal plumes around the human bodies (Figure 2 (b)). The airflow was upwards and towards the back. The airflow in the aisle (Figure 2 (c)) was upwards and to the front in the lower zone. The airflow pattern was similar to those obtained by Zhang et al., (2007).

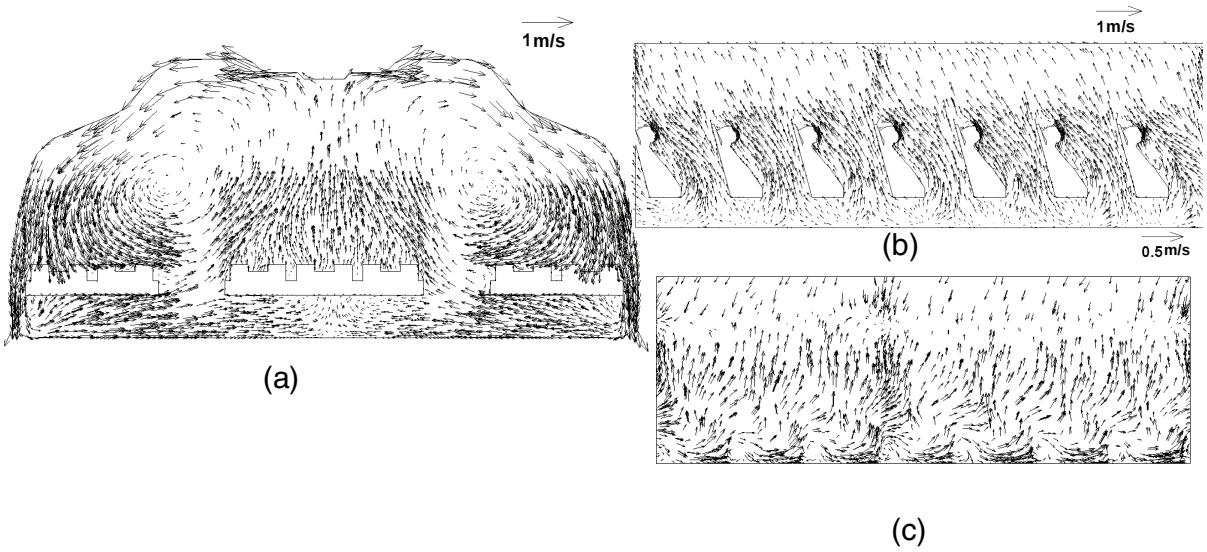

Figure 2. Airflow at the (a) cross-section (b) longitudinal plane passing through the infected passenger (c) longitudinal plane passing through the aisle

The unsteady transport of droplets exhaled from the breathing of the index passenger was studied using this steady state airflow and temperature solution as initial condition. Figure 3 shows the spatial and temporal distribution of the expiratory droplets in a perspective view. The breathing exhalation started at 1.85s and ended at 3.1s, therefore there were no droplets in the cabin before 1.85 seconds. The droplets were continuously exhaled with velocity of breathing (periodic) for this period. The droplets initially followed the breathing jet and then the bulk airflow in the cabin. The bulk airflow as shown in Figure 2 (b) moved the droplets upwards and towards the back. The strong lateral airflow current at the top made the droplets move along the top wall towards the sides. These droplets first reached the passengers seated on the window seats of the back row in around 10s. The droplets then moved to the aisle and to the row of the index passenger. This movement is in accordance with the airflow in the cabin. The total droplet fraction (df) defined as the total number of the droplets in the cabin divided by the total number of the droplets exhaled constantly reduced due to the droplet removal from the outlets and is shown in Figure 3. The local droplet fraction also reduced due to the droplet removal and dispersion in the domain. The total droplet fraction reached 12% in four minutes.

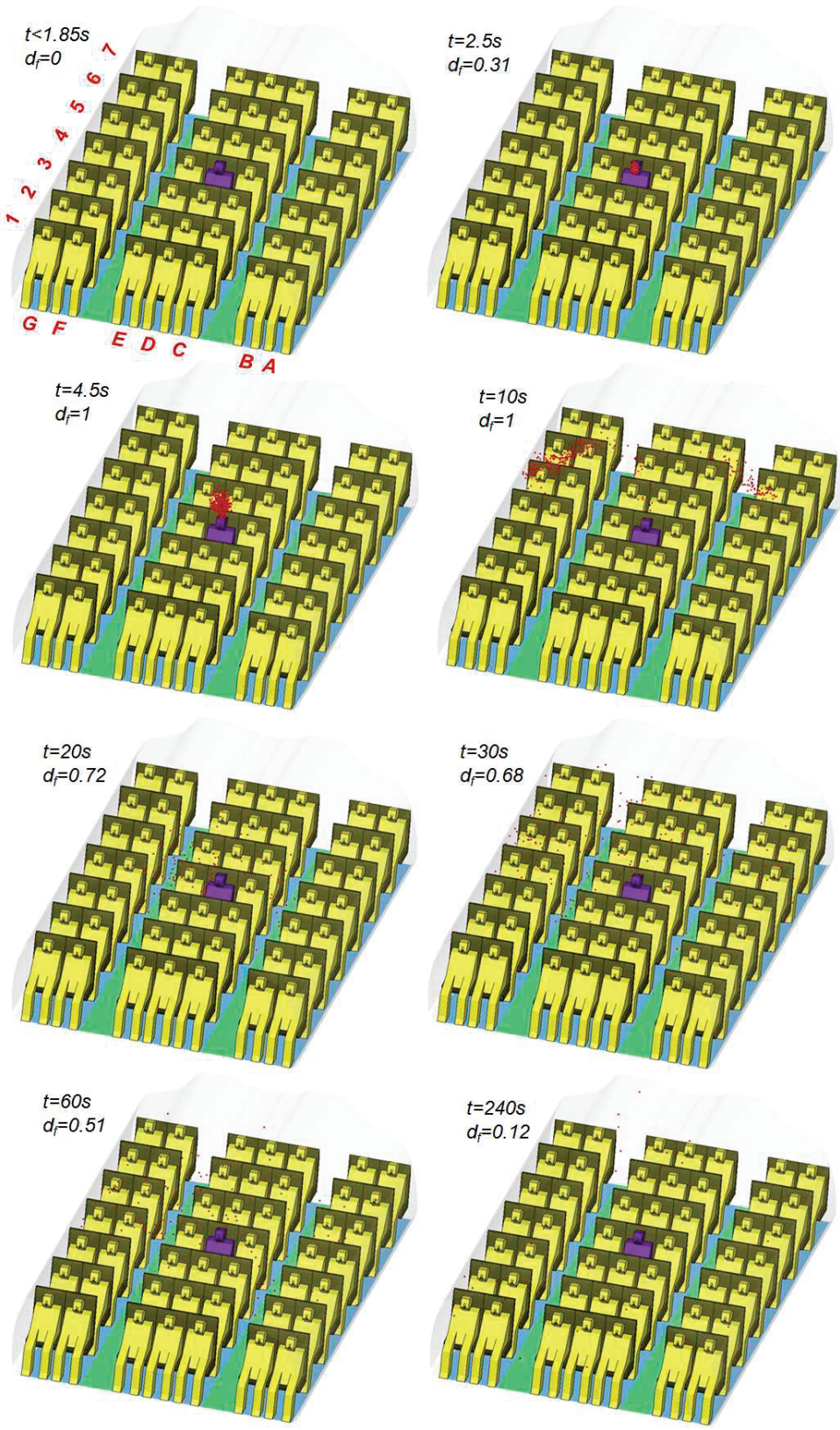

Figure 3. Spatial and temporal position of droplets in the cabin in a perspective view

Figure 4 shows the variation in the cumulative droplet fraction in the vicinity of the passenger seated on the window (A) seats. The cumulative droplet fraction till 10s was zero for all the passengers because the expiratory droplets did not reach any passengers. The cumulative droplet fraction then increased in the zones (e.g. 5A) where the droplet cloud reached. The rate of increment was higher for the initial period as the droplet cloud was dense. The droplet concentrations in the zones the cloud reached first were higher. It was observed that the droplets got well dispersed in the domain and the rate of change in cumulative droplet fraction was approximately same for all the passengers after 180s. Thus as stated in the methods a perfectly mixed model can be used after 180s. The differences in the prediction from the CFD simulation of 4 minutes and the semi-analytical model (a combined CFD model with perfectly mixed assumption after 3 minutes) were within 10%.

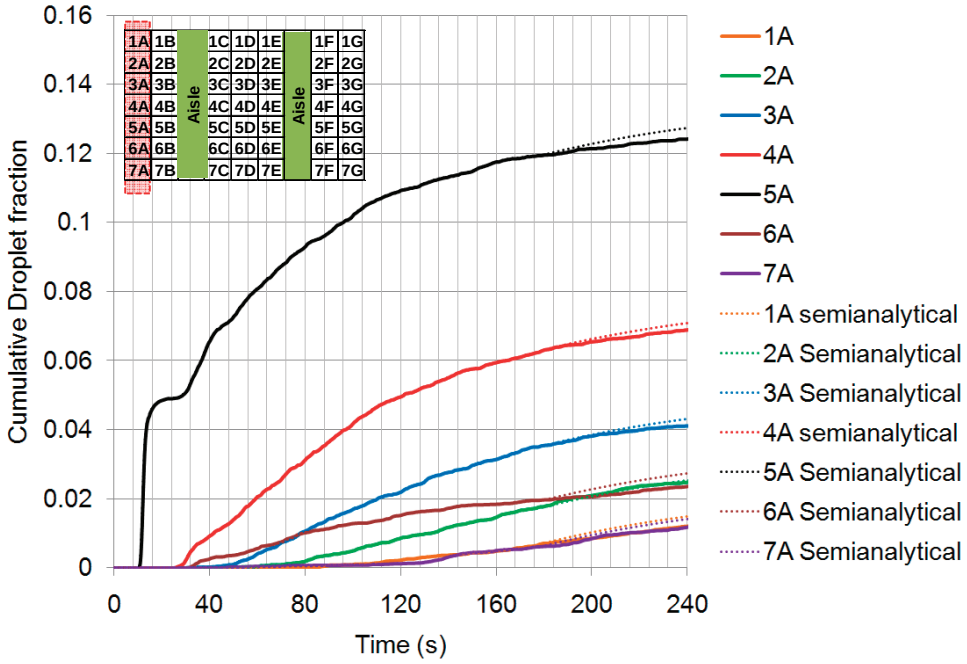

Figure 4. Variation in cumulative droplet concentration in the vicinity of passengers seated on A column

Figure 5 shows the variation in droplet fraction in the zones around passengers seated on window seat (A). It was found that trend of droplet fraction variation with time predicted by the CFD simulations for 10 consecutive breaths and by super-imposing the information obtained from a single breath exhalation simulation (The method of super-imposition) was similar. The differences in the values of the droplet fractions were substantial and could be due to the inherent transience of the flow, transient breathing flow and the random walk turbulent dispersion model used for the droplets. The trend of the variation in the droplet fraction predicted by both the methods was similar. Thus it is proposed that the method of super-imposition can be used to find out the droplet concentration variation for multiple exhalation cases.

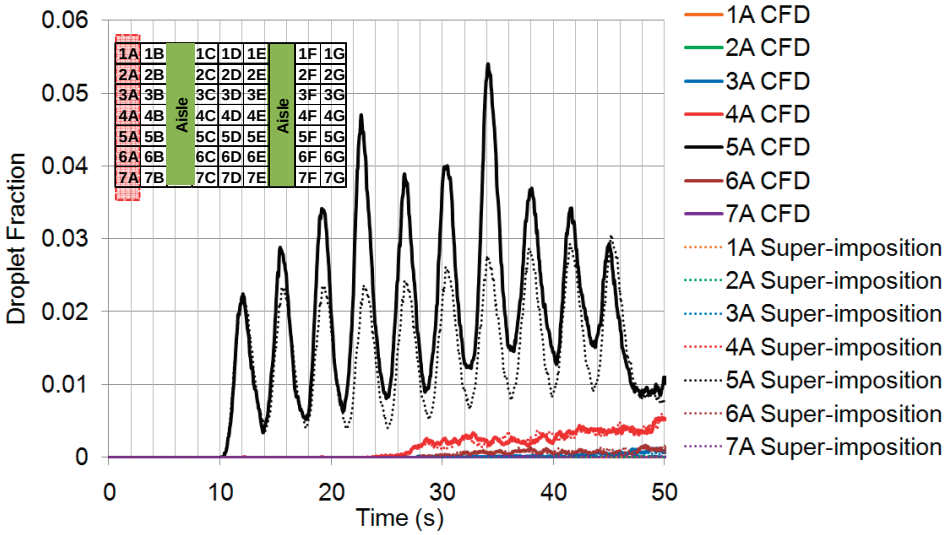

Figure 5. Comparison in droplet concentration predicted by the CFD simulations and the method of super-imposition

Finally the amount of inhaled droplets was calculated using equation (3). Figure 6 shows the amount of expiratory droplets inhaled by the passengers seated in the 3rd, 4th (index passenger row), and 5th row for a two hours of air travel. The amount of droplets inhaled ranged from 140 to 510 and was in accordance with the droplet movement and the airflow in the cabin. It should be noticed that all these droplets may not contain an active contagious agent, thus the results should be appropriately extended to quantify the risk.

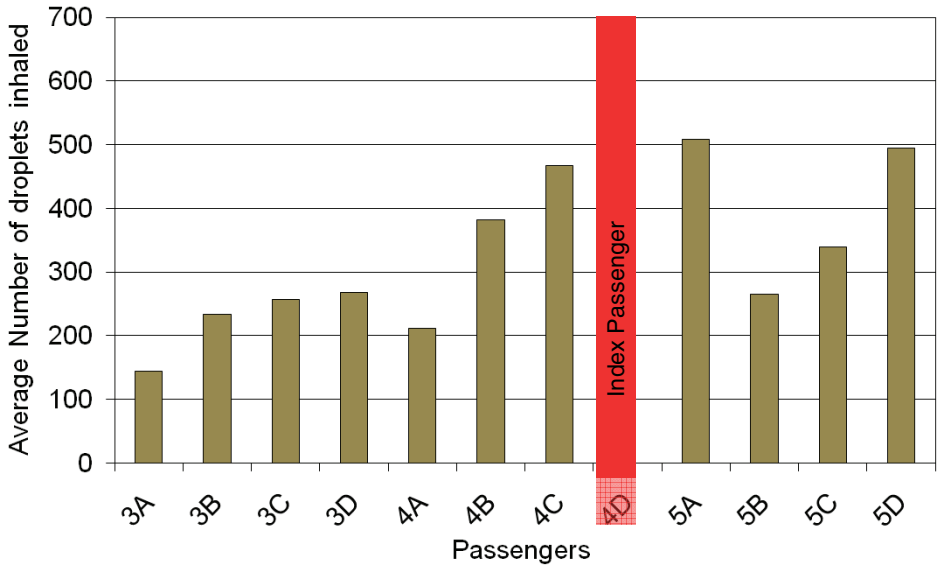

Figure 6. Average number droplets (exhaled by breathing) inhaled by the passengers during 2 hours of air travel

4. DISCUSSION

The present study developed the methods to calculate the amount of droplets inhaled by the passengers in an aircraft cabin. In order to quantify the risk of infection, this information needs to be integrated with the amount of active contagious agents contained in the droplets, threshold amount of contagious agents required to cause the infection, and the potency of the contagious agent. It should also be noticed that the present study is based on computational simulations and need to be validated against experiments.

5. CONCLUSIONS

The present study developed methods to predict the transport and inhalation of droplets exhaled by an index passenger in an aircraft cabin for realistic flight durations. The key conclusions from the study are

1. The CFD simulations indicated that the droplet movement was initially governed by the exhalation jet and then the bulk airflow in the cabin. The droplets got well mixed in the cabin in 3 minutes.
2. A perfectly mixed assumption can be used to extend the CFD data on droplet distribution beyond 3 minutes.
3. The droplets exhaled from various breathing exhalations at different times followed the same trajectory. Therefore, the droplet concentration information of a single exhalation transportation case can be superimposed with an appropriate time shift to obtain the droplet concentration information for multiple exhalations scenario.
4. The amount of droplets inhaled by the passengers was calculated by integrating the transient breathing profile with droplet concentration variation in the vicinity of the passengers.

ACKNOWLEDGEMENT

This work was supported by Boeing Commercial Airplanes. Boeing reserves all the copyrights to the work presented in the current article.

REFRENCES

Fabian, P., McDevitt, JJ., DeHaan, WH., Fung, ROP., Cowling, BJ., Chan, KH., Leung, GM. and Milton, DK. (2008) Influenza Virus in Human Exhaled Breath: An Observational Study. PLoS ONE, 3 (7), e2691.

Fairchild, CI. and Stampfer, JK. (1987) Particle concentration in exhaled breath. Am. Ind. Hyg. Assoc. J, 48(11), 948-949.

Gupta, J.K., Lin, C.-H., and Chen, Q. (2010) Characterizing exhaled airflow from breathing and talking. Indoor Air, 30 (1), 31-39.

Wan, MP., Sze To, GN., Chao, CYH., Fang, L. and Melikov, A. (2009) Modeling the Fate of Expiratory Aerosols and the Associated Infection Risk in an Aircraft Cabin Environment. Aerosol Science and Technology, 43(4), 322-343

Zhang, T., Chen, Q., and Lin, C.-H. (2007) Optimal sensor placement for airborne contaminant detection in an aircraft cabin. HVAC&R Research, 13(5), 683-696

Zhang, Z., Chen, X., Mazumdar, S., Zhang, T., and Chen, Q. (2009) Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mockup. Building and Environment, 44(1), 85-94.